Chapter 7
Synchronization Examples

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Source: Abraham Silberschatz, Peter B. Galvin, and Greg Gagne, "Operating System Concepts", 10th Edition, Wiley.

Outline

- Classic Problems of Synchronization
- Synchronization within the Kernel
- POSIX Synchronization
- Synchronization in Java
- Alternative Approaches
  - Transactional Memory
  - OpenMP
  - Functional Programming Languages

Classical Problems of Synchronization

- Bounded-Buffer Problem
- Readers and Writers Problem
- Dining-Philosophers Problem

Bounded-Buffer Problem

- *N* buffers, each one can hold an item
- Semaphore mutex initialized to the value 1
- Semaphore full initialized to the value 0
- Semaphore empty initialized to the value N
- Players
  - Producers
    - produce full buffers, wait for empty buffers
  - Consumers
    - produce empty buffers, wait for full buffers

Bounded Buffer Problem (Cont.)

- The structure of the producer process

```
do {
        //   produce an item
        wait (empty);
        wait (mutex);
        //  add the item to the  buffer
        signal (mutex);
        signal (full);
 } while (true);
```

Bounded Buffer Problem (Cont.)

- The structure of the consumer process

```
do {
        wait (full);
        wait (mutex);
        //  remove an item from  buffer
        signal (mutex);
        signal (empty);
        //  consume the removed item
} while (true);
```

Readers-Writers Problem

- A data set is shared among a number of concurrent processes
  - Readers – only read the data set; they do not perform any updates
  - Writers – can both read and write.
- Problem – How to allow multiple readers to read at the same time? Of course, only one single writer can access the shared data at the same time.
- Shared Data
  - Data set
  - Integer readcount initialized to 0. // number of readers
  - Semaphore mutex initialized to 1. // mutex on readcount
  - Semaphore wrt initialized to 1. // contention with a writer

Readers-Writers Problem (Cont.)

- The structure of a writer process

```
do  {
        wait (wrt) ;
        // writing is performed
        signal (wrt) ;
 } while (true);
```

Readers-Writers Problem (Cont.)

- The structure of a reader process

```
do  {
        wait (mutex) ;          // mutex: for updating and maintaining readcount
        readcount ++ ;
       if (readercount == 1)  wait (wrt) ; // the following readers do not wait(wrt)
        signal (mutex)

        // reading is performed

        wait (mutex) ;
        readcount  -- ;
        if (redacount  == 0)  signal (wrt) ;
        signal (mutex) ;
 } while (true)
```

•If a writer is in the critical section and n readers are waiting, then one reader is blocked on wrt and the other n-1 readers are blocked on mutex

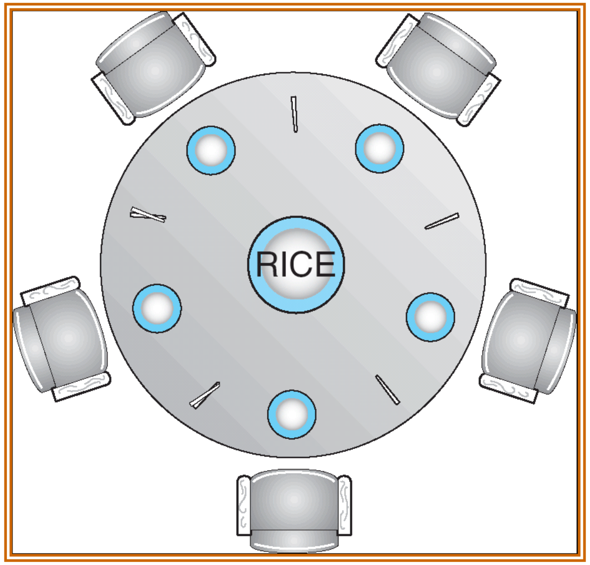
•On signal (wrt), we can wakeup a set of readers or a single writer

Reader-Writer Locks

- Some systems support reader-writer locks
- Using the reader-writer locks
  - Specify the lock mode: read or write
- Useful in the following situations
  - When it is easy to identify r/w access mode
  - More readers than writers

Dining-Philosophers Problem

- 5 Philosophers, spending their lives thinking and eating
- Get hungry ➔ try to get the chopsticks next to him
  - Pick up only one chopstick at a time
- Eat when he gets both
- Putdown both chopsticks when he is finished eating



Shared data

Bowl of rice (data set)

Semaphores chopstick [5] initialized to 1

Dining-Philosophers Problem (Cont.)

- The structure of Philosopher *i*:

```
do {
        wait ( chopstick[i] );
        wait ( chopstick[ (i + 1) % 5] );
            //  eat
        signal ( chopstick[i] );
        signal (chopstick[ (i + 1) % 5] );
            //  think
    } while (true) ;
```

Dining-Philosophers Problem

- The solution above may lead to deadlock
  - e.g., all philosophers pick up their left chopsticks
- Remedies
  - At most 4 philosophers
  - Pick up chopsticks when both are available
  - Odd philosophers: left, right; even philosophers: right, left.
- We will present a solution later

Monitor Solution to Dining Philosophers

Code for each philosopher:

```
DP.pickup(i);   // DP is the monitor
   …
   eat…
   …
DP.putdown(i);
```

Solution to Dining Philosophers (cont.)

A philosopher picks up chopsticks only when both of them are available

```
monitor DP
{
    enum { THINKING; HUNGRY, EATING) state [5] ;
    condition self [5];  //delay herself when she is hungry but unable to obtain the
    chopsticks

    void pickup (int i) {
        state[i] = HUNGRY;
        test(i);
        if (state[i] != EATING) self [i].wait;
    }

    void putdown (int i) {
        state[i] = THINKING;
            // test left and right neighbors
        test((i + 4) % 5); // allow the  philosopher on the left to finish her pickup
        test((i + 1) % 5); // allow the  philosopher on the right to finish her pickup
    }
```

Solution to Dining Philosophers (cont.)

```
    void test (int i) {
            if ( (state[(i + 4) % 5] != EATING) &&
            (state[i] == HUNGRY) &&
            (state[(i + 1) % 5] != EATING) ) {
                 state[i] = EATING ;
                 self[i].signal () ;
             }
     }

     initialization_code() {
           for (int i = 0; i < 5; i++)
           state[i] = THINKING;
    }
} // end of monitor
```

- ***No deadlock, but starvation is possible***

Synchronization Examples

- Kernel level
  - Solaris
  - Windows
  - Linux
- User level
  - POSIX
  - Java

Solaris Synchronization

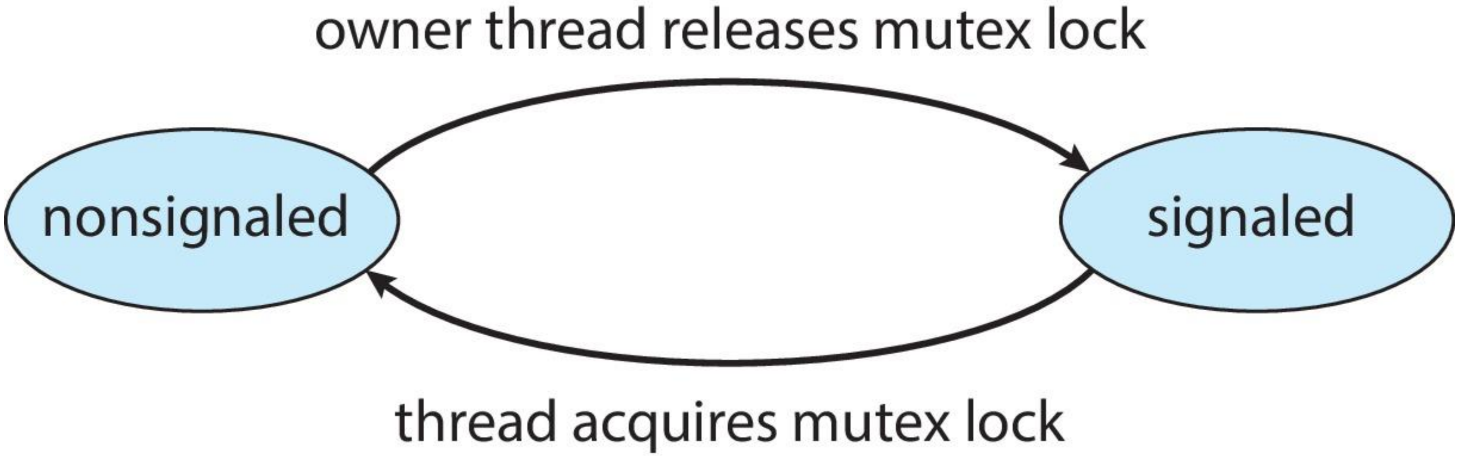
- Implements a variety of locks to support multitasking, multithreading (including real-time threads), and multiprocessing
- Uses adaptive mutexes for efficiency when protecting data from short code segments
  - If the lock holder is running ➔ busy waiting
  - Otherwise ➔ blocking
- Uses condition variables and semaphores for longer sections of code that require shared-data access
  - readers-writers locks are also provided

Windows Synchronization

- Uses interrupt masks to protect access to global resources on uniprocessor systems
- Uses spinlocks on multiprocessor systems
- Provides dispatcher objects which may act as either mutexes and semaphores
  - Object states: *signaled*, *non-signaled*
  - You can call the *KeWaitForSingleObject()* to wait for a dispatcher object
    - wait until another thread sets the object to the *signaled* state

Windows Synchronization

- Mutex dispatcher object



Linux Synchronization

- Linux
  - disables interrupts or uses spinlock for short critical sections

- Linux provides
  - semaphores
  - spinlocks
  - reader-writer locks/semaphores
  - atomic variables (atomic integers)

Linux Synchronization

- Atomic variables
  atomic_t is the type for atomic integer
- Consider the variables
  atomic_t counter;
  int value;

Atomic Operation	*Effect*
`atomic_set(&counter,5);`	`counter = 5`
`atomic_add(10,&counter);`	`counter = counter + 10`
`atomic_sub(4,&counter);`	`counter = counter - 4`
`atomic_inc(&counter);`	`counter = counter + 1`
`value = atomic_read(&counter);`	`value = 12`

POSIX Synchronization

- POSIX API is OS-independent
- It provides
  - mutex locks
  - semaphores
  - condition variables

- Widely used on UNIX, Linux, and macOS

POSIX Mutex Locks

- Creating and initializing the lock

```
#include <pthread.h>

pthread_mutex_t mutex;

/* create and initialize the mutex lock */
pthread_mutex_init(&mutex,NULL);
```

- Acquiring and releasing the lock

```
/* acquire the mutex lock */
pthread_mutex_lock(&mutex);

/* critical section */

/* release the mutex lock */
pthread_mutex_unlock(&mutex);
```

POSIX Mutex Locks API

```c
#include <pthread.h>

pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;

int pthread_mutex_init(pthread_mutex_t *restrict mutex,
                       const pthread_mutexattr_t *restrict attr);

int pthread_mutex_destroy(pthread_mutex_t *mutex);

int pthread_mutex_lock(pthread_mutex_t *mutex);

int pthread_mutex_trylock(pthread_mutex_t *mutex);

int pthread_mutex_unlock(pthread_mutex_t *mutex);
```

POSIX Semaphores

- POSIX provides two versions – **named** and **unnamed**
- **Named semaphores** can be used by **unrelated** processes by simply referring to the **semaphore's name**
- But, unnamed semaphores cannot

POSIX Unnamed Semaphores

- Creating an initializing the semaphore

```
#include <semaphore.h>
sem_t sem;

/* Create the semaphore and initialize it to 1 */
sem_init(&sem, 0, 1);
```

flag

Initial value

- Acquiring and releasing the semaphore

```
/* acquire the semaphore */
sem_wait(&sem);

/* critical section */

/* release the semaphore */
sem_post(&sem);
```

POSIX Named Semaphores

- Creating an initializing the semaphore:

```
#include <semaphore.h>
sem_t *sem;

/* Create the semaphore and initialize it to 1 */
sem = sem_open("SEM", O_CREAT, 0666, 1);
```

name flag mode Initial value

  - Other processes can access the semaphore by referring to the name **SEM**.

- Acquiring and releasing the semaphore:

```
/* acquire the semaphore */
sem_wait(sem);

/* critical section */

/* release the semaphore */
sem_post(sem);
```

POSIX Condition Variables

- Previously, **condition variables** are used within the context of a monitor
  - The monitor provides a **locking** mechanism to ensure **data integrity**
- POSIX is typically used in C/C++
  - These languages ***do not provide a monitor***
- Thus, POSIX condition variables are associated with a POSIX **mutex lock**
  - The mutex lock is used to provide mutual exclusion

POSIX Condition Variables (Cont.)

- Creating and initializing the condition variable

```
pthread_mutex_t mutex;
pthread_cond_t cond_var;

pthread_mutex_init(&mutex,NULL);
pthread_cond_init(&cond_var,NULL);
```

- Thread waiting for the condition **a == b** to become true:
  - The **mutex lock** is used to protect the data in the conditional clause (i.e., a and b) from a possible race condition
  - **pthread_condition_wait()** would ***release the mutex lock when waiting***

```
pthread_mutex_lock(&mutex);
while (a != b)
      pthread_cond_wait(&cond_var, &mutex);

pthread_mutex_unlock(&mutex);
```

POSIX Condition Variables (Cont.)

- Use **pthread_cond_signal()** to signal a thread waiting on the condition variable

```
pthread_mutex_lock(&mutex);
a = b;
pthread_cond_signal(&cond_var);
pthread_mutex_unlock(&mutex);
```

- Once the **mutex** is released, the signaled thread can re-own the mutex and returns from **pthread_cond_wait()**
- The signaled thread must put the conditional clause within a **loop** to **re-check the condition**, i.e., while (a!=b), after being signaled (see the previous slide)

Java Synchronization

- Java provides rich set of synchronization features
  - Java monitors
  - Reentrant locks
  - Semaphores
  - Condition variables

Java Monitors

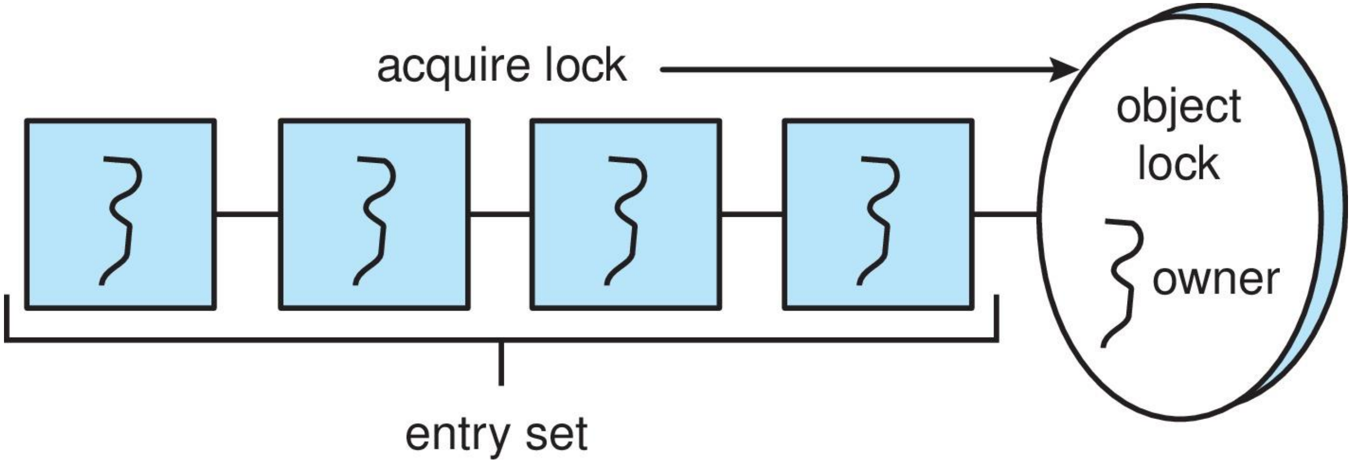
- Each Java object has an associated lock
- If a method is declared as **synchronized**, a calling thread must own the lock for the object
- If the lock is owned by another thread, the calling thread must wait for the lock until it is released
- Locks are released when the owning thread exits the **synchronized** method

Bounded Buffer – Java Synchronization

```
public class BoundedBuffer<E>
{
   private static final int BUFFER_SIZE = 5;

   private int count, in, out;
   private E[] buffer;

   public BoundedBuffer() {
      count = 0;
      in = 0;
      out = 0;
      buffer = (E[]) new Object[BUFFER_SIZE];
   }

   /* Producers call this method */
   public synchronized void insert(E item) {
      /* See Figure 7.11 */
   }

   /* Consumers call this method */
   public synchronized E remove() {
      /* See Figure 7.11 */
   }
}
```

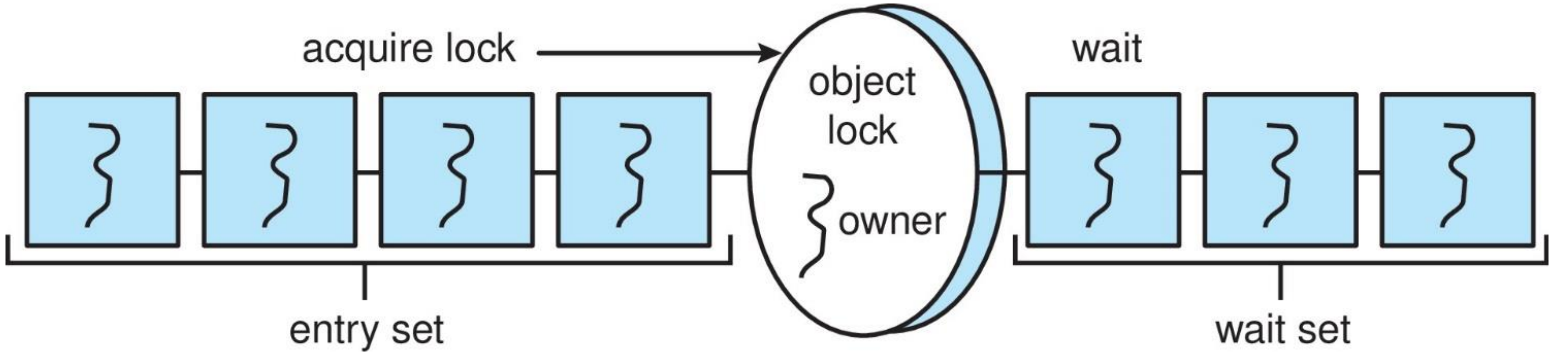
Java Synchronization

- A thread that tries to acquire an unavailable lock is placed in the object's **entry set**



Java Synchronization

- Similarly, each object also has a **wait set**.
- When a thread calls **wait()**
  - It releases the lock for the object
  - The state of the thread is set to blocked
  - The thread is placed in the wait set for the object



Java Synchronization

- A thread *T* typically calls wait() when it is waiting for a condition to become true.
- How does *T* get notified?
  - When another thread *S* calls **notify()**
    - Thread *T* may be selected from the wait set, and
      - *T* is moved from the wait set to the entry set
      - The state of *T* is changed from blocked to runnable
  - *T* can compete for the object lock after *S* releases the object lock
  - Once *T* gets the object lock again, **the wait() returns** and *T* can check whether or not the condition it was waiting for is now true

Bounded Buffer – Java Synchronization

```
/* Producers call this method */
public synchronized void insert(E item) {
   while (count == BUFFER_SIZE) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   buffer[in] = item;
   in = (in + 1) % BUFFER_SIZE;
   count++;

   notify();
}
```

Bounded Buffer – Java Synchronization

```
/* Consumers call this method */
public synchronized E remove() {
   E item;

   while (count == 0) {
      try {
         wait();
      }
      catch (InterruptedException ie) { }
   }

   item = buffer[out];
   out = (out + 1) % BUFFER_SIZE;
   count--;

   notify();

   return item;
}
```

Java Reentrant Locks

- Similar to **mutex locks**
  - *Reentrant*: the lock holder can acquire the lock again

```
Lock key = new ReentrantLock();

key.lock();
try {
   /* critical section */
}
finally {
   key.unlock();
}
```

The **finally** clause ensures the lock will be released in case an exception occurs in the **try** block.

Java Semaphores

```
Semaphore sem = new Semaphore(1);

try {
   sem.acquire();
   /* critical section */
}
catch (InterruptedException ie) { }
finally {
   sem.release();
}
```

Java Condition Variables

- Condition variables are associated with an ReentrantLock
- Creating a condition variable using **newCondition()** method of ReentrantLock

```
Lock key = new ReentrantLock();
Condition condVar = key.newCondition();
```

- A thread waits by calling the **await()** method, and signals by calling the **signal()** method
  - await() will **unlock** (the ReentrantLock) **and wait** atomically

Java Condition Variables

- Example
  - Five threads numbered 0 .. 4
  - Shared variable **turn** indicating which thread's turn it is.
  - A thread calls **doWork()** when it wishes to do some work.
    - But it may only do work if it is its turn
    - If not its turn, wait
    - If its turn, do some work for awhile ……
  - When completed, notify the thread whose turn is next.
  - Necessary data structures

```
Lock lock = new ReentrantLock();
Condition[] condVars = new Condition[5];

for (int i = 0; i < 5; i++)
   condVars[i] = lock.newCondition();
```

Java Condition Variables

```
/* threadNumber is the thread that wishes to do some work */
public void doWork(int threadNumber)
{
   lock.lock();

   try {
      /**
       * If it's not my turn, then wait
       * until I'm signaled.
       */
      if (threadNumber != turn)
         condVars[threadNumber].await();

      /**
       * Do some work for awhile ...
       */

      /**
       * Now signal to the next thread.
       */
      turn = (turn + 1) % 5;
      condVars[turn].signal();
   }
   catch (InterruptedException ie) { }
   finally {
      lock.unlock();
   }
}
```

signal the next thread only

Alternative Approaches

- Transactional Memory
- OpenMP
- Functional Programming Languages

Transactional Memory

- **Transaction**
  - A collection of instructions that performs single logical function
  - A transaction is performed either **in its entirety, or not at all**
    - **Atomic, all-or-none**
    - **Even in the presence of system failures!**
  - A transaction is terminated by
    - **Commit** : transaction successful (**in its entirety**), or
    - **Abort**: transaction failed (**not at all**)
  - Aborted transaction must be **rolled back** to **undo** any changes it performed
  - Example: funds transfer
- **Memory Transaction**
  - A sequence of memory read-write operations that are performed either **in its entirety, or not at all**

How to Rollback?

- Record **all modifications** made by a transaction
- Solution: **Write-Ahead Logging (WAL)**
  - **Log before write**
    - The **log** is maintained on **stable storage** (next slide)
    - Log must be completed before data updates
  - When a system failure occurs
    - Consult the log
      - If log contains **<Ti starts>** without **<Ti commits>**, **undo(Ti)**
      - If log contains **<Ti starts>** and **<Ti commits>**, **redo(Ti)**

Transactions

- Various types of storage
  - Volatile storage
    - Not survive system crashes
    - E.g., memory, cache
  - Non-volatile storage
    - Usually survive system crashes
    - E.g., disk, tape
    - Subject to failure
  - Stable storage
    - Never lose its data

Example

Transaction

init: a=0, b=1;

<T_1 start>

a = 10;

printf("%d\n",a);

if (a == 10)
b = 20;

<T_1 commit>
……

Log

<T_1 start>
T_1, a, 0, 10
T_1, b, 1, 20

Using Transactional Memory for Race Condition Problem

- Example: a function *update()* modifies shared data that uses **mutex** locks.

```
void update() {
        acquire();
        /* modify shared data */
        release();
}
```

- Alternative solutions: uses **transactional memory**
  - **atomic{*s*}**:the operations in ***S*** execute as a transaction

```
void update()
{
   atomic {
         /* modify shared data */
   }
}
```

Using Transactional Memory for Race Condition Problem

- If a **conflict** is not present // no race condition
  - commit changes
- When a **conflict** is detected // race condition
  - A transaction will roll-back to its initial state
  - And will re-run until no conflict
- Advantages
  - More easier for developer
  - No **locks** are involved, deadlock is not possible

Transactional Memory

- Implementation of transactional memory
  - **Software transactional memory**: software scheme
    - **Compiler** inserts instrumentation code inside transaction blocks
  - **Hardware transactional memory**: hardware scheme

OpenMP

- OpenMP: a set of compiler directives and an API that support parallel programming

- **#pragma omp critical**
  - Compiler directive provided by OpenMP
  - Specify the code region as a critical section

```
void update(int value)
{
    counter+=value;
}
```

```
void update(int value)
{
    #pragma omp critical
    {
        counter+=value;
    }
}
```

OpenMP (Cont.)

- Advantage of using the critical-section compiler directive in OpenMP
  - Easier to use than standard mutex locks

- Limitation
  - Deadlocks is still possible since the directive behaves like a mutex lock

Functional Programming Languages

- Most well-known languages are **imperative** (**procedural**) languages
  - **State-based**
  - Each state is represented by **variables** and **data structures**

- Instead, functional programming language do not maintain mutable state
  - Value of variable **cannot** be changed
    - so there are no state-change issues…
  - Thus, no race condition and deadlocks